

On communicating with semantic machines

Walter J Freeman

Department of Molecular & Cell Biology
University of California at Berkeley CA 94720-3200
<http://sulcus.berkeley.edu>

Abstract

Semantics is the essence of human communication. It concerns the manufacture and use of symbols as representations to exchange meanings. Information technology is faced with the problem of using intelligent machines as intermediaries for interpersonal communication. The problem of designing such semantic machines has been intractable because brains and machines work on very different principles. A solution to the problem is to describe how brains create meaning and then express it in information by making a symbol as a representation to another brain in pairwise communication. Understanding of the neurodynamics by which brains create meaning may enable engineers to build devices with which they can communicate pairwise, as they do now with colleagues, though not with words, but with shared actions.

Key Words: EEG patterns, intentionality, neurodynamics, phase transitions, semantics

1. Introduction

The most challenging of the three branches of semiotics is called semantics [5]. It deals with the relation between meanings and representations, a relation often referred to in artificial intelligence and philosophy as 'intention', 'aboutness' (a thought, belief or memory is 'about' something), or 'symbol grounding'. Computers are very good in the other two branches (syntactics, which is the relation of symbol to symbol as found in dictionaries) and pragmatics (the relations between symbol and action like those of traffic signals). They are inept in semantics. The reason for this ineptitude stems from deep differences between brains and computers. von Neumann [19] surmised nearly half a century ago:

"We have now accumulated sufficient evidence to see that whatever language the central nervous system is using, it is characterized by less logical and arithmetic depth than we are normally used to. ... Thus the outward forms of our mathematics are not absolutely relevant from the point of view of evaluating what the mathematical or logical language truly used by the central nervous system is. [W]hatever the system is, it cannot fail to differ considerably from what we consciously and explicitly consider as mathematics. p. 81"

Brains are exceedingly capable of grasping the salient features of complex situations and social relationships, which are captured in such words as 'value', 'significance', 'import', or 'bottom line', in a word, 'meaning'. It is my conclusion in this essay that meanings exist only in brains, where they take the place of the internal representations that computers use. My conclusion is based on research into the spatiotemporal patterns of active states of brains in animals, that accompany and support the animals' performance of the cognitive tasks involved in learning to respond appropriately to simple stimuli that signify events and circumstances that are vital to their welfare. I find that sensory cortices receive the information that the sensory receptors provide from stimuli, and that this information, once it has arrived in cortex, triggers the construction of activity patterns in brains that constitute the meaning of the stimuli. These patterns over-ride the sensory-driven information [4], which is then discarded, so that everything that an animal learns about its environment has been constructed within its brain from its own experiences.

In order to translate these findings into terms that engineers will require to emulate in hardware the performance of brains in wetware, some further consideration of the biological basis of meaning is required. A meaning state is an activity pattern that occupies the entire available brain [3]. The construction begins with formation within the animal of an activity pattern that embodies its immediate goal, such as food, shelter or a mate, the achievement of which requires acquisition of information from the environment. That information is got by intentional action into the environment, followed by sensory stimulation and learning from consequences of the action. A stimulus such as a light, an odor, or a tone contains information that serves to represent to the animal the state of its environment. It is a material object or process that is equivalent to a book, face, or gesture for humans. It is a part of the environment that has no meaning in itself. The French poet Paul Valéry [18] wrote:

"I have already explained what I think of literal representation; but one cannot insist enough on this: there is no true meaning of a text. No

author's authority. Whatever he may have wanted to say, he wrote what he wrote. Once published, a text is like an implement that everyone can use as he chooses and according to his means: it is not certain that the maker could use it better than someone else. p. 1597."

My analysis of brain activity patterns shows that sensory cortical activity patterns that are triggered by stimuli are selected by the stimuli but are determined by the history and context of the relations of the individual to the stimuli [4,5]. These brain activity patterns are states of meaning. They occur in the dynamic state space of a brain as trajectories of discrete steps marked by cortical phase transitions. The patterned active states are called wave packets [2]. The way in which they are made by the self-organizing brain dynamics that controls behavior is a pivotal topic in this essay.

The dynamics of brains that creates meaning can be emulated in computer models of brain function [4,12,15]. This step requires that a major problem be addressed: the relation between representation and meaning in brain function. The Shannon-Weaver information theory is representational, because it divorces meaning from information and therefore does not apply directly to brains. Shannon [16] wrote:

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. p. 380."

In Section 2, I sketch some of the principal elements of communication, as a basis for discussing a pathway toward solutions through a better understanding of the biological basis of meanings, which grows from behavioral actions. Meaning stems not from the rule-driven operations between symbols embedded within syntactical systems such as computers, nor from conventional 'computing with words'. It stems from shared actions. In Section 3, I summarize the main observations on sensory cortical wave packets. In Section 4, I enlarge the description to include the limbic system and the origin of intentional behavior. In Section 5, I take up the critical difference between linear and circular causality that underlies the distinction between deterministic and self-organizing systems. In Section 6, I discuss in more detail the relations between meaning and representation. In Section 7, I summarize.

2. Communication by representations

Operational discreteness is essential for communication in dialogue. A pair of brains can act, sense, and construct in alternation with respect to each other, just as dogs circle, and as two humans plan, speak, listen, and hear. Consider brains **A** and **B** interacting [Fig. 1], where **A-B** are parent-child, wife-husband, rabbit-dog, philosopher-biologist, neuroscientist -rabbit, etc. **A** has a thought that constitutes some meaning $M(a)$. In accordance with this meaning **A** acts to shape a bit of matter in the world (a trace of ink on paper, a vibration of air, a set of keystrokes on e-mail, movements of the face, etc.) to create a representation (a sign or symbol for humans, merely a sign for animals, in both cases, information) directed at **B**, $R(ab)$. **B** is impacted by this shaped matter and is induced by thought to create a meaning $M(b)$. So **B** acts to shape a bit of matter in accordance with $M(b)$ in a representation $R(ba)$, which impacts on **A** to induce $M(a+1)$.

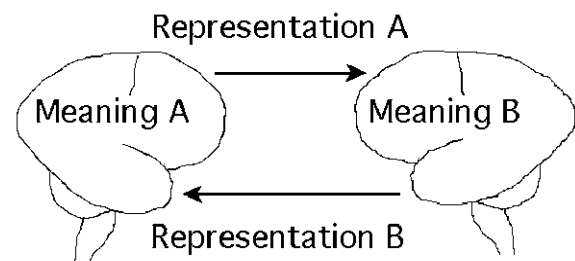


Fig. 1. The schematic shows the roles of representation in the communication of meaning between individuals by the exchange of information through use of representations. A method is proposed to replace one of the communicants with a machine

And so on. Already by this description there is implicit recognition of a discrete recurrent flow of conversation like the tides, so that meanings $M(i)$'s as constructions of thoughts become the internal active states, and the $R(ij)$'s as attributes of matter become the external representations. The interchange requires a coordinated succession of phase transitions in both communicants. By its relatively fixed nature an "external" representation can be used over and over, just as we use a letter, word, ideograph or equation. It cannot be said to contain or carry meaning, since the meanings are located uniquely inside **A** and **B** and not between them. The same R induces different meanings $M(i)$ in any other subject **C** who may intercept the transmission of a representation. The objects that are used to communicate are shaped by meanings that are constructed in **A** and **B** iteratively, and they induce the constructions of meaning in **B** and **A** alternately. If communication is successful,

then the internal meanings will come transiently into harmony, as manifested by cooperative behavior such as dancing, walking in step, shaking hands, exchanging notes, ringing bells, etc. Symbols persist in books and stone tablets, while minds fluctuate and evolve until they die.

3. Observations on the electric fields, the electroencephalogram (EEG)

A biological approach to the problem of meaning is to study the evolution of minds and brains, on the premise that animals have minds that are prototypic of our own, and that their brains and behaviors tell us what essential properties are common to animal and human minds. Experimental measurements of brain activity (EEG) that follows sensory stimulation of animals show that sensory cortices engage in construction of activity patterns in response to stimuli [2]. The operations are not those that are characteristic of computers, which include filtering, storing, retrieval, template matching, pattern completion, gradient descent, or correlation mechanisms. Each construct is by a phase transition, in which a sensory cortex switches abruptly from one basin of attraction to another, thereby changing one spatial pattern instantly to another like a succession of frames in a cinema.

The transitions in the primary sensory cortices (visual, auditory, somatic and olfactory [1]) are shaped by interactions with the limbic system, which establish multimodal unity, selective attention, and the intentionality of percepts. The interactions of the several sensory cortices and the limbic system lead to goal-directed actions in time and space. Each cortical phase transition involves synaptic change throughout the forebrain that constitute learning, so that a unified and global trajectory is formed cumulatively by each brain over its lifetime. Each spatial pattern reflects the content of past and present experience [5], that is, a meaning.

The most important experimental finding is that the neuroactivity patterns in sensory cortex, which form during perception of conditioned stimuli by the animals, are not invariant with respect to unchanging physicochemical stimuli. The brain activity patterns are found to change slightly and cumulatively with any change in the significance of the stimuli, such as by changing the reinforcement, or with the addition of new stimuli [4]. From numerous tests of this kind the conclusion is drawn that brain patterns reflect the value and significance of the stimuli for the animals, not fixed memory traces.

Each pattern forming in response to the presentation of a stimulus is freshly constructed by

chaotic dynamics in the sensory cortex, in cooperation with input from the limbic system that implements the supporting processes of attention and intention. It expresses the history, existing state, and intent of the animal rather than the actual incident stimulus. The patterns cannot be representations of meanings of stimuli, either. They are observable manifestations from the material substrate of the meanings that are induced by stimuli, or that emerge from self-induced instabilities in the sensory and limbic systems. Their trajectory constitutes the evolution of a brain in its growth of experience [13]. Similarly, a semantic device must be given opportunity to practice, experience, and grow in abilities to communicate.

The mechanism by which the formation of a wave packet is triggered is of particular interest. When an animal or human receives sensory information, it is carried not by any small number of axons from receptors but by a massive barrage of action potentials. A glimpse of a face, for example, includes all of the detectors for motions, contours, colors, and binocular disparities of the face, and also whatever background against which the face is glimpsed, such as a crowd, a factory or a battlefield. The process in mammals involves a dozen or more specialized areas in each sensory cortex that process the sensory information, with multiple feedback pathways among them.

Despite this enormous complexity, recognition occurs within half a second. The mechanism suggested by EEG analysis is that an entire sensory cortex is destabilized by input that is gated by a rapid eye movement (a microsaccade), or its equivalent in other sensory systems such as a sniff or a finger motion. When it is destabilized, the cortex jumps from one state to another. The transition is completed within 3-7 msec of onset [4, 7]. It is followed within 25-35 msec by the formation of a spatial pattern of amplitude modulation [AM, Fig. 2] of a chaotic carrier wave that persists for 80-100 msec. The AM pattern is accompanied by a spatial pattern of phase modulation [PM, Fig. 2] that is radially symmetric with a fixed phase velocity in all directions. The PM pattern is measured by fitting to it a cone in the 2 dimensions of the brain surface [7].

These two features, the AM and PM patterns, serve to characterize the spatial and temporal location, size, duration and content of the wave packet that is triggered by sensory input. The AM pattern manifests the meaning of the stimulus, not the stimulus in itself, because the AM pattern changes when the context or significance of the stimulus is changed [4] [Fig. 2, right]. In contrast, the location and sign of the apex (maximal lead or lag) of the PM

cone are random variables that do not reflect the properties of the stimulus that evoked it or its meaning for the subject [Fig. 3] [1,4,7].

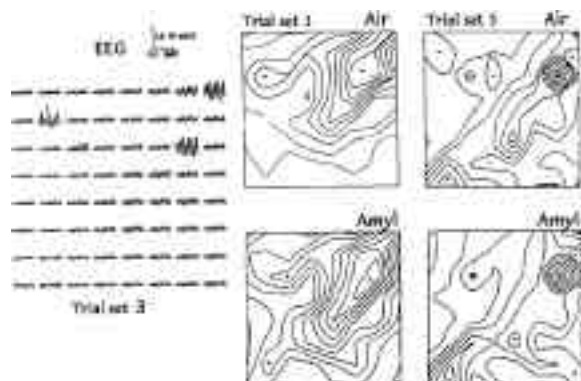


Fig. 2. Left. EEG traces from an 8x8 electrode array (4x4 mm) in 100 msec burst from olfactory bulb after band pass filtering in the gamma range (20-80 Hz). Middle. Spatial AM patterns from RMS amplitudes on first trial set with control and odor amyl acetate. Right. Two weeks later in session 3 the stimuli were the same, but the AM patterns had evolved to new forms, showing that they are not representations. They are context dependent and individualized for each animal, and they change with variations in the reinforcement.

The randomness of the sign implies that the apex cannot signify a pacemaker for the oscillation, which in any case is aperiodic. The proposed explanation is that the phase gradient manifests the formation of a wave packet by a 1st order phase transition [9], for which the location of the apex reveals the site of nucleation, and the velocity conforms to the finite rate of spread of the state change in a distributed medium, in the case of cortex by the conduction velocities of axons running parallel to the pial surface [7].

The phase gradient shows that the populations of neurons in the wave packet are not oscillating in phase at zero lag, but that they do so with leads or lags that increase with distance from the apex. This feature provides a soft boundary condition for the wave packet, which can be specified by the half-power diameter. The mode and 95% inclusion diameters are shown by circles in Fig. 4, which are superimposed on a diagram of the rabbit forebrain as seen from above. Wave packets having these properties were found in all of the sensory cortices examined. The 8x8 electrode arrays were placed on the primary sensory receiving areas, as shown by the rectangles indicating the size and locations of electrode arrays. The 64 electrodes were used to record the EEGs from the sensory cortices, in order to calculate the AM and PM patterns in the cortical activity.

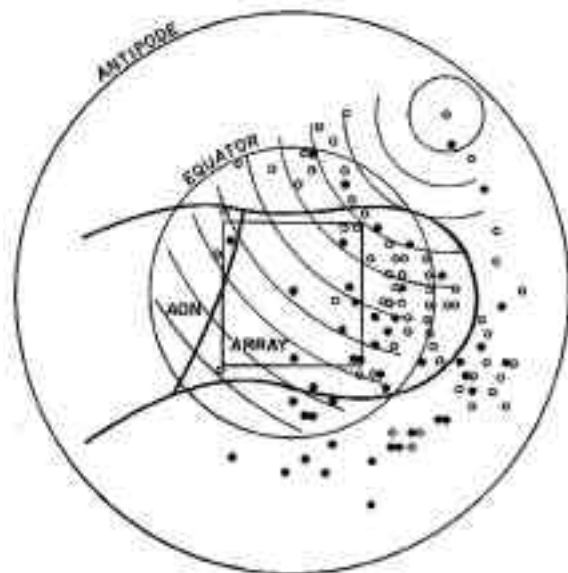


Fig. 3. Phase distributions were measured with respect to the phase of the spatial ensemble average at the surface of the olfactory bulb and fitted with a cone in spherical coordinates. The sketch is a projection of the outline of the bulb as it would appear on looking through the left bulb onto the array on the left lateral surface of the bulb. A representative set of isophase contours is at intervals of 0.25 radians/mm. The locations of the apices of the cones on the surface of the sphere (2.5 mm in radius) are plotted from the center of the array to the antipode. The square outlines the electrode array. The standard error of location of points was twice the radius of the dots. From Freeman and Baird [6].

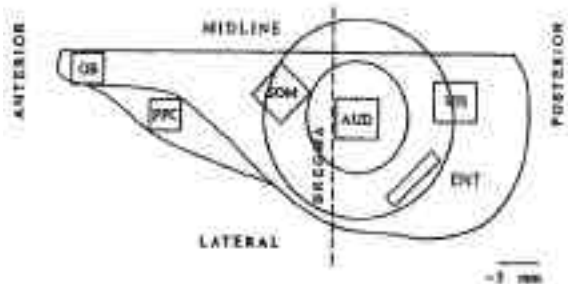


Fig. 4. The outline shows the left cerebral hemisphere of the rabbit as seen from above. The rectangles show the approximate locations of the 8x8 arrays placed on the olfactory bulb (OB), prepyriform cortex (PPC), somatomotor cortex (SOM), auditory cortex (AUD), and visual cortex (VIS), and a 2x8 array on the entorhinal cortex (ENT). The inner circle shows the modal diameter of phase cones. The outer circle shows the diameter including 95% of cases. The vertical line is the zero stereotaxic reference. Diameter inner circle: 15 mm. Adapted from Barrie et al. [1].

4. Neural base of intentional action

its chemical state. It is also shaped by neurohormones from nuclei in the brain stem. The emergent pattern impacts the brain stem and spinal cord, leading to stereotypic searching movements that are adapted to the immediately surrounding world. Feedback from the muscles and joints to the somatosensory cortex provides confirmation whether the intended actions are taking place. The impact of the movements of the body on sensory input is conveyed to the visual, auditory and olfactory systems. All of these perceptual constructs, that are triggered by sensory stimuli and are dependent on prior learning, are transmitted to the limbic system, specifically to the entorhinal cortex, where they are combined. When, for example, an animal detects an odor of food, it must hold the immediate memory of the concentration, move, take another sniff, and compare the two concentrations in order to decide which way to move next. The difference in strength has no meaning, unless the animal has a record of where it was when it sensed the first concentration, which way it moved, when the second sample was taken, and to where. This information provides a basis for determining distance and direction in its environment from itself to its intended goal. These basic operations of intentional behavior are properties of the limbic system. The same requirements hold for all distance receptors, so it is understandable that evolution has led to multimodal sensory convergence that performs space-time integration on the multisensory percept, the Gestalt, not on its components prior to their assembly. These operations are already commonplace in robotics, though less so their integration into goal states.

In the description thus far the flow of neural activity is counterclockwise through loops from sensory systems to motor systems, then through proprioceptive and exteroceptive loops outside the brain back to the sensory systems. Within the brain there is a clockwise loop that sustains the flow of activity constituting refference (the leftward arrows from "motor systems" through "entorhinal cortex" to "sensory" systems, then rightward to close the loops). When a motor act is initiated by the limbic system, it issues a command as an activity pattern descending into the brain stem and spinal cord. Copies of this activity pattern are sent clockwise along these internal pathways to all of the sensory systems by the entorhinal cortex. These 'efference copies' [17] prepare the sensory processors for the impact on the sensory systems of the movements of the eyes, head, ears, and body and, most importantly, the efference copies sensitize the sensory cortices selectively by shaping their attractor landscapes to respond only to stimuli that are appropriate for the goal toward which the action has been directed. The efference copy has also been denoted as a 'sense of effort' [3]. They are

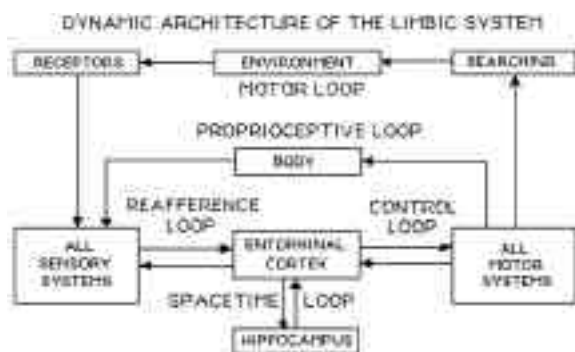


Fig. 5. A schematic diagram summarizes the main elements in the dynamics of intentional behavior to aid in the design of a KIV device capable of intentional action, including semantic communication. From Freeman [6].

For example, hunger is an emergent pattern of neuroactivity that expresses the requirements of brains and bodies for metabolic fuel and building material. It induces a phase transition in the neural populations of the forebrain under the influence of sensory stimuli from the gut and the brain's own chemoreceptors for

the essence of selective attention. These concepts are familiar in feedback control; they need to be generalized in the context of intentional behavior.

5. Linear versus circular causality in self-organizing systems

The conventional view of sensory cortical function holds that stimuli activate receptors, which transmit information to sensory cortex through a linear causal chain, leading eventually to a motor response to the initiating stimulus. Contrariwise, modeling with nonlinear dynamics shows that the stimulus is typically not the initiating event. Rather it is the search for the stimulus that arises in conjunction with an evolving goal in the limbic system, which emerges in a recurrent manner from prior search and its results. This is circular causality at the level of intentional behavior [10].

Much lower in the hierarchy of brain organization is another instance of circular causality. This is the creation of the wave packet in the primary sensory cortex, which consists of the destabilization of a pre-existing mesoscopic state by the introduction of intense barrages of microscopic sensory input. In this case the transition from a prior basin of attraction to a new one, which has been facilitated by limbic modulation, is guided by the sensory input that activates a learned nerve cell assembly comprising a small subset of cortical neurons. The input from the receptors includes both the expected stimulus and the massive receptor discharge evoked by everything that is in the background. The total receptor input forces the instability and triggers the phase transition, and the nerve cell assembly that is activated by the expected stimulus selects the basin of attraction that captures the cortical system. Then the entire domain of the primary sensory cortex transits to the pattern that emerges as the system converges to the attractor in the basin, which in the words of Haken [10] "enslaves" the whole set of cortical neurons by acting as an "order parameter". This new active state has been characterized by Ilya Prigogine [14] as a "dissipative structure", that constitutes, in his words, the "emergence of order out of chaos".

The similarity of the properties of neural activity in the various parts of the limbic system to those in the primary sensory cortices [1,4] indicates that populations of neurons there also maintain global attractors, which are accessed by nonlinear phase transitions, and which are responsible for the genesis of goal states, their motor patterns controlling goal-directed actions, and the reafference patterns that prepare the sensory cortices for the consequences of those actions.

The construction of a device that can simulate the creative dynamics of the brain has been based primarily on the dynamics and architecture of the olfactory system, both in software [8,12] and in hardware [4,15]. The basic unit of the construction is a neuron population called a KO set, that is roughly equivalent to an average neuron [2]. Its time-dependent dynamics is governed by a linear 2nd order ordinary differential equation that is evaluated by fitting its solution as a sum of two exponentials to derive the coefficients for the rate of rise of the impulse response and the passive decay rate of the membranes. Its input is provided by lines that terminate in simulated synapses represented by gain coefficients that are subject to change by learning, and its output is bounded by a static nonlinear gain curve, which is the derivative of the sigmoid curve [6] relating dendritic current amplitude to pulse density output of the population. An interactive population of excitatory neurons is called a KI_e set, and is made by feedback connections between two excitatory KO_e sets in positive excitatory feedback. Similarly a KI_i set is made by feedback connections between two KO_i sets in positive feedback. KI sets have zero and non-zero point attractors and can generate sustained excitatory and inhibitory biases. A KII set is made by negative feedback connections between a KI_e set and a KI_i set. It has both point and limit cycle attractors.

The interconnection and interaction of three KII sets with distributed feedback delays forms a $KIII$ set, that is capable of aperiodic, nonconvergent, sustained output governed by a chaotic attractor, in addition to outputs governed by point and limit cycle attractors. The nonlinear gain curve, which is the derivative of the sigmoid function, governs pulse density in relation to dendritic current density [2,4,8]. The attractor landscape determines the spatial patterns of EEG of sensory cortices, which are experimentally observed from 8x8 arrays of recording electrodes with a simulation using a $KIII$ set embodying an 8x8 array of coupled KII sets in the OB layer of a $KIII$ set [8]. Each node in Fig. 5 is equivalent to a $KIII$ set. The cooperative synaptic interactions among them support a KIV set, which is responsible for primitive forms of intentional behavior.

6. A hypothesis on the relations of meanings and representations

The idea is proposed that representations are formed by the motor systems through the forward, counterclockwise flow of neural activity. The motor commands are formed at the mesoscopic level by the interactions of neurons and neuronal populations, under the 'enslaving' influence of the global attractor

landscape of the KIV set. The commands place the motor systems of the brain stem and spinal cord into appropriate basins of attraction. The representations emerge as spatiotemporal patterns of activity in the effectors of the body (the musculoskeletal apparatus, the autonomic nervous system, and the neuroendocrine nuclei), which respond to the volleys of action potentials from motor neurons at the microscopic level, i.e. single motor units activated in concert. The movements of the body, supported by the autonomic and neuroendocrine back-ups, express the internal meaning states by gestures, vocalizations, shaped objects, etc. These actions change the sensory inflow of the actor in a goal-directed manner. The actions elicit sensory feedback not only to the individual in action. The representations, as intended, activate patterns of receptor discharge in other beings, that place their sensory cortices into the expected basins of attraction. The receivers likewise create patterns of meaning, that lead to up-dates in their limbic systems, re-formation of motor commands, and behaviors that re-transmit representations to the original actor. Thereby, the circular causal chain is maintained between two or more communicators.

The internal clockwise back flow of neural activity serves as an order parameter to modulate and shape the neural activity patterns of the sensory cortices, which transmit the states of their neural populations before and after the expected inputs have occurred, and also if they do not occur as expected, or at all. Modulation comprises not only the reafference but also the exteroceptive and proprioceptive feedback as well. I infer that the organisms constructing and transmitting representations cannot know their meanings until the sensory consequences have been delivered to their own limbic systems. More generally, a poet, painter, or scientist cannot know the meaning of his or her creation until after the act has been registered as an act of the self, nor until the listeners and viewers have responded with reciprocal representations of their own, each with meaning unique to the recipients.

Why do brains work this way? Animals and humans survive and flourish in an infinitely complex world despite having finite brains. Their mode of coping is to construct hypotheses in the form of neural activity patterns and test them by movements into the environment. All that they can know is the hypotheses they have constructed, tested, and either accepted or rejected [5,13]. The same limitation is currently encountered in the failure of machines to function in environments that are not circumscribed and drastically reduced in complexity from the real world. Truly flexible and adaptive intelligence operating in realistic environments cannot flourish without meaning.

This assembly of interacting wave packets may be seen as a mechanism supporting consciousness, which, in the neurodynamic view, is a spatiotemporal pattern of activity that occupies the entire forebrain. It is an internal state variable that has a trajectory composed of a sequence of transitory states that correspond to awareness. Its regulatory role transcends that of the operator in a thermostat, although they share the properties that instantiate the difference between the state of the environment and expectation, such as a sensed temperature and a set point, and that initiates corrective action respectively by intentional action or by turning a heater on or off. The difference is that the simple machine state variable has little history and no capacities for learning or determining its own set point, but the principle is the same: the internal state is a form of energy, an operator, a predictor of the future, and a carrier of information that is available to the system as a whole. The feedback device is a prototype, an evolutionary precursor, not to be confused with awareness, any more than tropism in plants and bacteria is to be confused with intentionality. In animals and humans, the operations and informational contents of this global state variable constitute the experience of causation.

7. Summary

Semantics deals with the relation between meanings and representations, widely known as intention, 'aboutness', or the symbol grounding problem. Brains obtain information about their environments through the consequences of the intentional actions that they execute using their bodies.

Studies of the spatiotemporal patterns of electroencephalographic (EEG) potentials that are induced by conditioned stimuli in the primary sensory and limbic cortices of trained animals have shown that the information thus obtained is used to construct meanings and is then discarded. Computers use representations for information processing and symbol manipulation, but brains have no internal representations. They deploy dynamic neural operators in the form of neural activity patterns that construct and implement meaning but not information. Observers can describe these patterns as information, but that does not imply that the brains do so, or need to. Brains construct external representations of their meanings in the form of shaped objects or movements as their mechanism for expressing their internal states. Examples are facial expressions and gestures in animals and words in humans. Those material constructs are made with the intent to elicit meaning in other brains, but they have no meanings in themselves and do not carry meanings

as if they were buckets or placards. Meanings can only exist in brains, because each meaning expresses the entire history and experience of an individual. It is an activity pattern that occupies the entire available brain, constituting a location in the dynamic state space of a brain. EEG data indicate that neural patterns of meanings in each brain are based in mesoscopic wave packets that follow trajectories in discrete steps. Each step is demarcated by a 1st order phase transition that enables formation of spatiotemporal patterns of chaotic oscillations in the gamma range. Amplitude modulation of the carrier wave is the mode of expressing meanings. These wave packets do not represent external objects; they embody and implement the meanings for each individual of his or her interactions with the environment.

Engineers who propose to make semantic machines are faced with the task of defining meaning, which at present exists only in brains, and then with the task of learning how to design machines that can make or cause meaning in themselves. The requirements on network models to simulate the chaotic dynamics of brains include global though sparse connectivity, continuous time dynamics, and distributed spatial functions in two-dimensional arrays of nonlinear integrators. Digital hardware may suffice to emulate the biological functions of sensory cortex in brains by use of nonlinear difference equations as in KIII sets [8], provided that the problems can be solved of attractor crowding and numerical instabilities that inhere in digital representations of chaotic dynamics [12]. Digital simulation is a useful step toward analog simulation in VLSI [15], by means of which to attain the computational speed that will be required for real-time operation of the device. In this way, the next step toward machine meaning can be to use a KIII model of a sensory cortex as an interface between the unconstrained real world, which is infinitely complex, and the finite state automaton that will rely on a dedicated digital computing system as the main support for its artificial intelligence. That is, a model from brain dynamics can provide the eyes and ears for a conventional computer, that can enable the device to interface effectively with the infinitely complex environment that it will share with its designers, and about which it can communicate its views.

Acknowledgment

This work was supported in part by a NASA grant (NCC 2-1244). A preliminary version of this work appeared in Freeman [5].

References

- [1] Barrie JM, Freeman WJ, Lenhart M. Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in neocortex of rabbits. *J. Neurophysiol.* **76**: 520-539, 1996.
- [2] Freeman WJ. *Mass Action in the Nervous System*. New York: Academic, 1975.
- [3] Freeman WJ. *How Brains Make Up Their Minds*. New York: Columbia University Press, 2001.
- [4] Freeman WJ. *Neurodynamics. An Exploration of Mesoscopic Brain Dynamics*. London UK: Springer-Verlag, 2000.
- [5] Freeman WJ. A neurobiological interpretation of semiotics: meaning, representation, and information. *Inform. Sci.* **124**: 93-102, 2000.
- [6] Freeman WJ, Baird B. Relation of olfactory EEG to behavior: Spatial analysis. *Behav. Neurosci.* **101**:393-408, 1987.
- [7] Freeman WJ, Barrie JM. Analysis of spatial patterns of phase in neocortical gamma EEGs in rabbit. *J. Neurophysiol.* **84**: 1266-1278, 2000.
- [8] Freeman WJ, Chang H-J, Burke BC, Rose PA, Badler J. Taming chaos: Stabilization of aperiodic attractors by noise. *IEEE Trans. Circuits & Syst.* **44**: 989-996, 1997.
- [9] Freeman WJ, Rogers LM. Fine temporal resolution of analytic phase reveals episodic synchronization by state transitions in gamma EEGs. *J. Neurophysiol.*, **87**: 937-945, 2002
- [10] Haken H. *Synergetics: An Introduction*. Berlin: Springer-Verlag, 1983.
- [11] Herrick CJ. *The Brain of the Tiger Salamander*. Chicago IL: University of Chicago Press, 1948.
- [12] Kozma R, Freeman WJ. Chaotic resonance: Methods and applications for robust classification of noisy and variable patterns. *Intern. J. Bifurcation & Chaos* **10**: 2307-2322, 2001.
- [13] Piaget J. *The Child's Conception of Physical Causality*. New York: Harcourt, Brace, 1930.
- [14] Prigogine I. *From Being to Becoming: Time and Complexity in the Physical Sciences*. San Francisco: WH Freeman, 1980.
- [15] Principe JC, Tavares VG, Harris JG, Freeman WJ. Design and implementation of a biologically realistic olfactory cortex in analog VLSI. *Proc. IEEE* **89**: 1030-1051, 2001.
- [16] Shannon CE. A mathematical theory of communication. *Bell System Tech. J.* **27**:379-623, 1948.
- [17] Sperry RW. Neural basis of the spontaneous optokinetic response. *J. Comp. Physiol.* **43**: 482-489, 1950.
- [18] Valery P. Oeuvres. Etablie et annotee par Jean Hytier. Paris, Gallimard, p1597, 1957.
- [19] von Neuman J *The Computer and the Brain*. New Haven CT: Yale University, 1958.